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Energetically Modified Cement (EMC) and Ordinary Portland Cement (OPC) - A Comparison

By

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Preface

This report is mainly based on evaluation of test results from investigations at the Division of Structural Engineering and the Center of High Performance Cement, CHPC, at Luleå University of Technology, Sweden, and at SINTEF, Trondheim, Norway.

During the compilation of the report, viewpoints and comments have been given by Dr Vladimir Ronin, EMC Development AB, and Adjunct Professor at Luleå University of Technology.

A first edition of the report was issued in February 2000. We thank those who have cared to make comments in order to improve this second edition.

Luleå in November 2000

Lennart Elfgren Jan-Erik Jonasson

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Summary

The purpose of this document is to compare the essential properties of Energetically Modified Cement (EMC) with those of Ordinary Portland Cement (OPC). The main comparison is made with EMC-50, where 50 % of the binder consists of quartz sand.

The overall conclusion is that EMC cement has production properties (setting time, workability), compressive strength and frost resistance in line with concrete produced with Ordinary Portland Cement (OPC).

In areas especially important for engineering structures (gas and liquid permeability) where durability is a key factor, EMC cements perform superior to OPC. The areas in which EMC cements performed better are important in many applications such as bridges, tunnels, roads etc as well as marine constructions, constructions for chemical industries, structures for nuclear and other hazardous wastes.

1. The EMC Technology

The blending of ordinary Portland cement (OPC) with various fillers such as blast slag, fly ash and limestone has existed for many decades, some, such as blast furnace slag, for more than 70 years.

It is well known that the binding capacity of OPC is directly tied to, among other important circumstances as available space and local humidity, the degree of water's penetration into the cement particles. Normally in concrete, depending on the water to binder ratio, the OPC particles only hydrate in average about 50% of their potential and thus only about 50% of the potential binding capacity of OPC is used.

Energetically Modified Cement (EMC) is produced by high intensive grinding/activation of ordinary Portland cement (OPC) together with different types of fillers. This surface activation of the Portland clinker minerals such as C_3S and C_2S is believed to create a network of sub-micro cracks, micro defects and dislocations of the cement particles that provide deeper penetration of the water into the cement particles. Accordingly, in EMC cement a greater percentage of the potential binding capacity is utilised.

Tests of the microstructure of EMC cement have been performed by Norcem, the Norwegian subsidiary of Heidelberger Zement of Germany, the 3rd largest cement producer in the world, Heidelberger Zement of Germany and SGAB Analytica, Sweden. The tests consisted of X-ray diffraction (XRD) and Scanning Electron Microscopy-Backscattered Electron imaging analysis (SEM-BSEI).

In these tests fine SiO_2 particles have been detected. The EMC method for the blended cement EMC-50 involves a high intensive vibration milling of fine quartz particles together with OPC, which may possibly imply an activation of the mineral surfaces leading to enhanced reactivity, reduced surface crystallinity and increased solubility at alkaline conditions, which are prevailing in cement paste.

The changes of the mineral particle properties obtained are most significant with respect to the puzzolanic activity in hydrated cement, which have an effect on the strength development of the concrete produced by this process. Consequently, a comparable strength development has been shown for concrete made from EMC-50 blended cement as for concrete mixes made of pure OPC.

The result is that in addition to being able to significantly increase the amount of traditional fillers being used, new, inert fillers, such as fine quartz sand can also be activated by the EMC method.

To put this in perspective, OPC particles generally have a fineness of about 350-400 m^2/kg (Blaine). If the OPC particles were ground very fine, the surface would increase and a higher reactivity up to a certain time would be the result. The cost for this type of grinding is usually regarded as too high in comparison with the expected result.

It is also well known that if quartz sand was ground ultra fine it could also be activated using traditional grinding methods (ultra fine SiO_2 from the metallurgical industry is a widely known and used additive to enhance the performance of cement in concrete). However, the cost of the mentioned grinding methods is also very high.

In summary, what is unique about the EMC method, is that it represents an economical way to achieve an increased reactivity with the opportunity to replace part of the OPC with other, more environmental friendly products, like quartz sand.

It should be stressed that no additives are used in the EMC process. EMC cements incorporate only ingredients that have already been used in concretes for almost a century (Portland clinker minerals/Portland cement and traditional fillers such as slag, fly ash and limestone and fine fractions of aggregates used in concrete, such as quartz sand).

A general description of cement and concrete is given by e.g. Bye (1999), Taylor (1997) and Neville (1973). The EMC process was developed at Luleå University of Technology and at EMC Development AB from 1994, Ronin et al (1994, 1995, 1997), Jonasson et al (1996), Rao et al (1997), Groth et al (1999), Hedlund et al (1999), and Johansson et al (1999).

In this paper, primarily, some results from investigations at SINTEF in Trondheim, Norway (Dahl and Haugen 1998, 1999), and at Luleå University of Technology will be summarised. Comparisons will also be made of tests performed by Holderbank (Switzerland), Heildelberger Zement (Germany), Blue Circle (UK), Betongindustri (Sweden) subsidiary of Heildelberger Zement, and Norcem (Norway) subsidiary of Heildelberger Zement.

2. Standard requirements

All cement or binder products to be used in concrete production have to fulfil demands as to

- Fresh and hardening concrete
- Strength development
- Durability

The purpose behind these requirements is that the end product, the concrete, must be able to

- Be handled as required on site or at a pre-cast factory
- Have a strength development to be able to fulfill safely a production cycle
- Have a final strength to be able to carry a predefined bearing capacity
- Have an adequate lifetime for the structure in question

In the following EMC concretes will be checked with regard to the standard requirements. More details about these are given in appendix 1.

3. Summary of test results

3.1 Overall comparison

The EMC cements selected for comparison with OPC are designated “EMC-50” and “EMC-20”, respectively. EMC-50 contains 50 % of OPC and 50 % of quartz sand, and EMC-20 contains 80 % of OPC and 20 % of quartz sand. From the viewpoint of high replacement of OPC, the EMC-50 cement is the most interesting to analyse.

The comparative studies have been performed at the Centre for High Performance Cement at Luleå University of Technology (Sweden) and at SINTEF Civil and Environmental Engineering, Cement and Concrete (Norway) during the period 1996 – 1999. The obtained data clearly show the compliance of the test results with those obtained by SINTEF and Luleå University of Technology.

The SINTEF-MEMO entitled “EMC Binders - Brief Outline of Test Results” is presented in appendix 2, and some of the conclusions from appendix 2 are directly quoted in the report.

Evaluation of the test results performed by SINTEF have, when applicable, been done in accordance with the European prestandard prEN 206, which uses the "equivalent performance" (or k-value) concept to assess the effect of additions on the concrete. The k-values express the total effect (physical and chemical) of an addition with respect to a given EMC-concrete property, relative to OPC. The test results from SINTEF are summarized in Table 3.1 and show that both EMC cements perform equal to or better than OPC in all tests except carbonation.

Table 3.1. Summary of test results at SINTEF for EMC-blends (Sellevold, 1998).

Parameter	**Standardised method of testing**	**k-value of quartz filler in EMC-blends 4)**
Properties of fresh concrete	NS 3663 (ISO 4109) NS 3664 (prEN 1915-13)	1)
28 days compressive strength	ISO 4012	2)
Capillary suction and porosity	SINTEF-procedure, KS 70 110	> 1.0
Carbonation	"Accelerated SINTEF Carbonation Test"	0.5-0.8 (EMC-20) 0.5-0.6 (EMC-50)
Water vapour diffusion	Nordtest Build 443	> 1.0
Resistance to water penetration	ISO/DIS 7031	> 1.0
Chloride permeability	Nordtest Build 443, ASTM C 1202 and Nordtest Build 355	> 1.0
Frost resistance	Nordtest Build 376	3)

1) The test showed that concrete production of the EMC-mixes did not differ significantly from reference OPC-mixes.

2) The tests showed that EMC-20 performs better than OPC and EMC-50 performs in a range around OPC.

3) The tests showed that frost resistance may be achieved with proper air entrainment, in line with normal procedures for OPC-concrete.

4) k-value of 1 shows equal performance, k-value greater than 1, better performance, and k-value lower than 1, lower performance of the EMC than the reference OPC.

Note that, generally speaking, *all k-values higher than 0 are remarkable*, since k = 0 is the usual assumption for inert filler. The exception is the heat of hydration, where k value lower than 1 indicates better performance (see Appendix 2), because generally speaking, lower heat liberation is usually preferable for the concrete structures.

More detailed information are given in the sections below.

3.2 Fresh and hardening concrete

Results on fresh and hardening concrete are presented in tables A3-1 to A3-3 in app. 2.

The concretes produced with EMC cement (EMC-50) are characterized by the same values of the *final setting time* as the reference OPC, about 4.0 – 4.5 hours.

Workability, which is a vital parameter from the viewpoint of construction work performance, does not differ from OPC-concrete**.** Concrete mix design regarding the adjustment of the water reducing admixtures required for EMC-50 is similar to that required for OPC-concrete.

Heat of hydration. The k-values for the quartz filler in the EMC-50 regarding the heat of hydration measured for the concretes with water to binder ratios from 0.45 to 0.60 are in the range 0.56 – 0.94, i.e. that heat of hydration for EMC-50 is lower than for OPC. This means that the temperature in a structure using EMC cement will be decreased, which most likely will be beneficial for the risk of thermocracking.

3.3 Strength development

Results on strength development are shown in figures A3-1 to A3-2 in appendix 3. These results indicate that EMC-50 performs in line with or better than OPC concretes. For the 28 day strength the k-values are from 1.1 to 1.3 for different water to binder ratios. This shows that concretes with EMC-50 match the main criterion for the structural design.

Regarding the strength development between 28 and 90 days of curing EMC-50 shows somewhat lower increase of strength in comparison with OPC concretes (for w/ B = 0.60), 7.5 % and 11.8 %, respectively. This phenomenon is known for the traditional concrete produced with silica fume, which reacts quite completely within 28 days, reducing the longer-term strength gain. The similar effect could be observed for the fine OPC contra a coarse one, and for C_3S rich OPC contra one with higher C_2S (and lower C_3S) contents.

Tests have shown that the long-term strength of concrete mixes of EMC cements remains above the 28 days strength, but the long-term strength increase is lower than the use of concrete with OPC. Fortunately, this seems to have no consequence on the frost-thawing resistance, see figure A3-9 in appendix 3. (Although figure A3-9 reflects tests done with EMC500 cement containing 95% OPC and 5% silica fume, the tendency is equally relevant for EMC-50).

3.4 Durability

Tests of properties essential to durability have been performed on *water transport*, *chloride transport*, *frost resistance*, and *carbonation*, respectively.

Water transport

Three methods showing different aspects of water transport were used: 1) water penetration, 2) capillary suction and 3) water vapor diffusion.

Water penetration is a controversial method commonly producing great deviation in the results – but it is also in very common use. The present results also give large deviations, but the results as a whole indicate no significant difference between OPC and EMC-mixes, i.e. the k-values are in approximate unity.

Capillary suction measures the water suction rates after pre-drying the samples at 105°C. This is a very severe treatment and the method therefore also measures the robustness of a concrete to such harsh treatment which produces severe micro-cracking in the structure. The results were very good for the EMC-mixes. All of them showed greater resistance than the best OPC, implying k-values well over unity, which corresponds to higher resistance numbers in figure A3-3. This makes EMC-concretes more effective from the viewpoint of liquid (and gas) penetration.

Water vapor diffusion involves pre-drying of samples at 40°C for 7 days, and then measures the steady state transport rate in a gradient from 100 % to 50 % relative humidity. As for the capillary suction the results were very good for the EMC-blends, with k-values well over unity, which corresponds to lower diffusion coefficients in figure A3-4.

Chloride transport

Three, in principle, different methods were used: 1) chloride migration in a potential gradient of 12 Volt, 2) chloride diffusion in a concentration gradient, and 3) ASTM C 1202-94, where the electrical charge passed through a sample at 60 Volt gradient is measured over 6 hours.

The ASTM-test gave k-values well above unity for all the EMC-mixes, which in table A3-4 in appendix 3 corresponds to very low and low permeability compared with moderate or high permeability for OPC concretes.

The chloride migration test gave k-values in the ranges 1.1 – 1.8 (EMC-20) and 1.0 – 1.3 (EMC-50), which in figure A3-5 in appendix 3 corresponds to lower apparent diffusion coefficients for EMC concrete compared with the OPC concrete.

The chloride diffusion test gave k-values in the ranges 1.2 – 2.2 (EMC-20) and 1.2 – 1.7 (EMC-50), which in figure A3-6 in appendix 3 corresponds to lower effective diffusion coefficients for EMC concretes compared with the OPC concrete.

The overall results from the 6 transport tests give a consistent conclusion in spite of the widely differing test principles: The rate of transport of both water and chloride is equal to or reduced compared to reference OPC-mixes for both EMC-blends ($k \geq 1$). EMC-mixes have slightly greater total porosities as discussed above, but this increase is apparently more than compensated for by a more finely divided and/or less continuous pore structure.

Frost resistance

Frost/salt-scaling resistance was tested according to the Swedish SS 137244 method, which is used extensively in Europe. It is important to note that no concrete with w/b-ratios of 0.45 or higher is expected to pass the test without proper air entrainment. Therefore, in the present case, air entrainment at a 4 – 5 % level was used in separate mixes for all binders, but only for w/b = 0.45 and 0.60.

The results for w/b = 0.45 is shown in figure A3-7 in appendix 3, where it can be seen that the EMC concretes as well as the reference OPC concrete are below the level “acceptable”, i.e., they both performed better than “acceptable”. The overall conclusion of these tests is that that frost/salt-scaling resistance can be achieved for EMC concrete by air entrainment in line with OPC concrete.

Carbonation

It is noted that carbonation is only an issue for external concrete constructions or part of structures exposed to alternating high humidity and dry conditions due to other reasons. In such cases durability damage (carbonation in concrete followed by corrosion of reinforcement) may occur if the concrete has relative low cement content and high water to binder ratio, a situation that account for no more than 20% of all concrete applications.

Carbonation tests were carried out according to a SINTEF procedure, which is very accelerated by drying the samples at 45°C for 7 days (after 28 days water curing), before exposure to air containing 3 % CO_2 (100 times natural concentration) and 60 % relative humidity. There are no standard methods with general international acceptance available. Carbonation depth was measured periodically up to 16 weeks.

The results showed somewhat greater carbonation depths for EMC-20 mixes compared to OPC-mixes (k-values of 0.5 – 0.8), while for EMC-50 mix the k-values were about 0.5-0.6).

These results are difficult to interpret directly in terms of practical implications, because the particular test method used exaggerate real life conditions. The depth of carbonation generally follows the drying front into the concrete (wet concrete carbonates very slowly because the water in the pores delay CO_2-penetration). Thus, the drying rate controls the carbonation rate. For pre-dried concrete the carbonation rate is mainly controlled by CaO available for carbonation, which again depends on the amount of OPC which supplies the CaO. In the EMC-case the OPC and thus the CaO content is strongly reduced, but the increased tightness to water vapor transport is expected to offset this effect to an unknown extent. The pre-drying procedure employed here (45°C, 7 days) has accelerated the natural drying and therefore strongly accelerated.

It is considered that this is an unrealistic procedure relative to actual conditions. Probably the resistance against carbonation is sufficient for the use of EMC cements in realistic situations. This is supported by:

1. The historical field experience is good with other blended cements that, like EMC, have reduced CaO content and lower performance on the designed carbonation test and which show no deterioration relative to OPC due to carbonation (and compared to which EMC has better carbonation results).

2. The resistance to water and chloride penetration is higher for EMC cements.

3. The finer and thus tighter pore structure of EMC cement.

4. EMC Cements with Traditional Fillers

While this report so far has focused on quartz sand as the filler for EMC cement, a number of tests have also been done using the traditional fillers of limestone, fly ash blast, and furnace slag.

Tables 4.1 to 4.3 below show the results of such tests performed by Blue Circle (UK), Heildelberger Zement (Germany) and Appleby Group (UK). These results confirm that using the EMC technology, the filler content can be increased by 30 % to 75 % depending on filler used.

Furthermore, the tables 4.3 and 4.4 show significant increases in strength development where the same amount of filler is used in the EMC treatment compared with the same amount added to OPC. These results imply that the filler content can be substantially increased.

***Evaluation of tables 4.3 and 4.4*:**
A review of the combined results of tables 4.3 and 4.4 indicates that

- EMC cement containing slag volumes of about 50% obtains 3 and 7 days strength development comparable to pure OPC.
- EMC cement containing slag volumes above 70% performs in line with the requirements of ENV-197-1 regarding the general strength development requirements for 42.5 strength class cement.

EMC can achieve performance with cement containing 75% slag comparable to that, which is achieved with slag content below 50% for conventional OPC-slag products.

Table 4.1. Tests with limestone microfiller performed by Blue Circle.

Type of mixture	**Compressive strength, MPa for limestone content, % by cement weight**		
	0	30	40
EN-mortar, 2 days	18.6	24.6	19.7
EN-mortar, 28 days	53.5	54.9	37.8
Concrete*, 2 days	16.0	13.4	9.5
Concrete*, 28 days	48.8	37.3	32.5

*) Concrete with the binder content 300 kg/m^3 and w/B ratio 0.48

Table 4.2. Tests with fly ash performed by Blue Circle.

Type of mixture	Compressive strength, MPa for fly ash, % by cement weight			
	0	30	40	50
EN-mortar, 2 days	18.6	23.8	18.6	14.4
EN-mortar, 28 days	53.5	54.9	46.8	39.7
Concrete*, 2 days	16.0	13.4	10.5	--
Concrete*, 28 days	48.8	43.7	35.1	--

*) Concrete with the binder content 300 kg/m^3 and w/B ratio 0.48

Table 4.3. Tests with blast furnace slag performed by Appleby Group for concrete with cement content 350 kg/m^3 and water to binder ratio 0.54.

Type of mixture	Slag content, %	Compressive strength, MPa for curing time, days		
		3	7	28
OPC	0	30.2	36.1	56.1
OPC+slag	50	19.0	28.0	54.0
EMC with slag*	50	29.0	37.1	60.9
EMC with slag**	75	19.9	33.9	50.9

*) Composition contained 50% OPC and 50% of blast furnace slag
**) Composition contained 25% OPC and 75% of blast furnace slag

Table 4.4. Tests with blast furnace slag performed by Heidelberger Zement and EMC on Heidelberger materials for EN mortar.

Type of mixture	Slag content, %	Compressive strength, MPa for curing time, days		
		2	7	28
OPC	0	30.1**	39.8**	47.7**
OPC+slag	43	16.1**	30.5**	51.8**
EMC with slag	43	19.5**	38.4**	55.6**
EMC with slag	70#	10.1*	36.8*	52.5*
EMC with slag	70##	10.0*	36.5*	52.7*
EMC with slag	80###	8.0*	30.2*	49.9*

#) The 70% slag composition contained 25% OPC and 5% Silica fume.
##) The 70% composition contained 25% OPC and 5% fine quartz sand and
###) The 80% slag composition contained 15% OPC, 80% slag and 5% Silica fume.
*) The data obtained by EMC on Heidelberger materials
**) The data obtained by HZ

(The reference OPC used in the Heidelberger case is the company's Leimen cement, well known for high 2-day compressive strength, which is relevant where rapid hardening performance is required.)

5. Applications of EMC cement.

From the application point of view two main areas have to be distinguished: concrete for ordinary buildings and concrete for civil engineering constructions.

Summarising the data from the previous sections indicates that EMC concretes match the requirements for both areas. Especially important aspect for the concrete aimed for buildings is the very smooth surfaces, which reduces the need for after treatment. It is also valuable to mention that, in addition, concrete mixes with the use of EMC-50 has a much lighter colour than can be obtained with OPC concretes.

The concrete for civil engineering applications has an especial demand for a considerably improved durability (the required life time for bridges in Sweden is up to 100 years according to the Swedish Road Administration). There are also demands on low gas and liquid permeability and low risk of thermocracking. EMC concretes are in line with all these mentioned requirements and perform better than OPC concretes in several areas.

Specifically, reduction of the tricalcium silicate (C_3S) in EMC blends reduces the heat of hydration, and as a consequence the temperature rise in the structure will decrease, which most likely will be beneficial for the risk of thermocracking.

Finally, the reduction of tricaclium aliminate (C_3A) in EMC blends is in favour for formation of ettringite, as the access of aluminate decreses. This in addition with the improvement of resistance to liquid penetration will give a concrete with higher sulphate resistance.

6. Environmental considerations

Following the recently concluded Kyoto Protocol to the United Nations framework Convention on Climate Change, many countries have accepted legally binding commitments to reduce the emission rates of gases contribution to global warming by the year 2010.

One of the results of this Protocol is the increased importance of adding the evaluation of environmental impact of new and existing technologies to those of product performance/ quality and economics.

About 7% of the world's carbon dioxide emission is attributable to the Portland cement industry. As such, the Portland cement industry is one of the largest single producers of carbon dioxide emissions, one of the gases primarily responsible for global warming.

It is also well known that each ton of production of OPC is accompanied by the release of about one ton of carbon dioxide and that about half of this comes from the decarbonisation of limestone in the kiln and the other half from energy consumption, primarily in the kiln.

It follows that the only way in which the cement industry can achieve meaningful reductions in carbon dioxide emissions is via the reduction of Portland clinker production and the increased use of fillers (the cement industry does not believe that more than about 2-3% further reduction in energy consumption is possible in OPC production).

EMC cements containing microfillers could significantly improve the environmental profile of the cement industry in the world since the EMC technology provides a possibility to introduce into cement manufacturing non-traditional fillers like quartz sand, fine fraction of granite, and fine fractions of recycled concrete. It can also significantly increase the percentage of traditional fillers (e.g. blast-furnace slag, limestone, fly ash).

By being able to replace about 50% of the OPC production with fillers, the EMC technology, reduces carbon dioxide emission by about 40%. Global application of the technology means that the cement industry, one of the world's largest producers of carbon dioxide could contribute as much as 3% to global reductions of carbon dioxide emissions and thus become one of the most important contributors to the goal of reducing global warming. (By comparison, the global goal of the Kyoto Protocol is about 5%).

It should be considered as a unique opportunity to reduce pollution and minimise costs of cement production in the 21st century.

7. Economic Considerations

While it is not strictly the task of the authors to evaluate the economic elements of the EMC technology, this is such an important issue that some general observations are appropriate.

EMC cements are produced through inter-grinding of relatively high cost Portland cement and relatively low cost fillers to the extent 50%.

Thus the uniqueness of the EMC technology is not only its technical performance and the prospect of reduction in carbon dioxide emissions, but that this can achieved with a significant reduction in production cost.

8. Practical Experiences with EMC Cement

EMC cement has been produced in small scale since 1995 and a number of reference objects have been built (see Appendix 4).

The most recent of these reference objects was a bridge in Northern Sweden for the Swedish State Road Building Commission. A report from this project has been attached hereto as Appendix 5 authored by licentiate of technology Hans Hedlund.

These reports show that practical experiences and laboratory tests are consistent.

9. Review of concrete and cement industry tests of EMC cement

During the last 3.5 years EMC cements with different types of microfiller (quartz sand, blast furnace slag, fly ash, etc) have been tested by the leading cement and concrete companies: Holderbank (Switzerland), Heildelberger Zement (Germany), Blue Circle (UK), Betongindustri (Sweden) subsidiary of Heildelberger Zement, and Norcem (Norway) subsidiary of Heildelberger Zement. The main objective of these tests was to compare the performance parameters of EMC cements and concretes (fresh concrete, strength development, durability, etc) and Ordinary Portland Cement.

10. Conclusions

EMC cements in concrete performed in line with concrete produced with ordinary Portland cement (OPC) with regard to production properties (setting time, workability) and compressive strength.

In areas especially important for engineering structures (gas and liquid permeability) where durability is a key factor EMC cements perform superior to OPC. The areas in which EMC cements performed better are important in many applications such as bridges, tunnels, roads) as well as marine structures, constructions for chemical industries, structures for nuclear and other hazardous wastes, etc.

With respect to carbonation measured with “accelerated test” EMC cements performed lower than OPC but in line with traditionally blended cements. These tests are not considered representative of real life experiences. In this respect, it is well known, that traditionally blended cements e.g. blast furnace slag cements have shown no real life adverse effects from carbonation compared to OPC. On the contrary they have had excellent performance in practice for more than 50 years in Holland, Germany, UK, etc.

Significantly reduced gas and liquid permeability of EMC concretes should have additional positive impact on the resistance against carbonation.

Applied throughout the cement industry, the EMC technology would make one of the most important contributions to achieving reduction on global warming from carbon dioxide emissions.

The uniqueness of the EMC technology is not only its technical performance and the prospect of reduction in carbon dioxide emissions, but that this can be achieved with a significant reduction in production cost.

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Appendix 1. Standard requirements for cement and binder product for use in concrete

According to generally accepted practice, cement and concrete performance shall comply with European codes as ENV 197-1:1992 “Cement - Composition, specifications and conformity criteria” and prEN 206 “Concrete - Performance, production and conformity”.

The following parameters were chosen for a comparative study between EMC and OPC:

Fresh and hardening concrete

Setting properties. Concrete should be delivered to the customer with required consistency. To meet this requirement the initial setting time of the concrete (cement) should not be less than 45 min. When the concrete has been placed in a mould it should gain the strength fast enough to provide remoulding as soon as possible. For this matter the final setting time of the concrete (cement) should not be longer than 420 min.

Workability. This parameter characterizes the consistency (flowabilty) of fresh concrete mixtures, the ability to fill a mould full of reinforcement without voids and with a minimum amount of vibration. Due to restrictions regarding the water to cement ratio for the concretes used in different exposure conditions super plasticisers are used as a fluidising agent.

Heat of hydration. Cement releases heat when it reacts with water (an exothermic reaction). Usually, for massive structures this will give rise to temperature gradients which can cause cracking of the concrete. In order to avoid this problem in Scandinavia, e.g. for engineering objects allowed only so called Moderate Heat Liberating Cement (with substantial reduced amount of C_3A), the price of this cement is about 20% higher than OPC.

Hardened concrete.

Strength. Strength is the most important parameter of concrete because it determines the loading capacity of the concrete structure. Concrete strength is also well correlating with deformability (E-modulus) and usually also with durability.

All engineering codes prescribe the 28 day strength as strength requirement for construction design. The early age strength (usually 1, 2 and 7 days) is of importance only in the case of special objects when the speed of the process is a critical issue.

Strength development after 28 days (90 and 180 days) is practically never prescribed as a required parameter. As an exception dam constructions can be mentioned.

Porosity. Concrete porosity (total porosity and pore size distribution) has a significant influence on the mechanical properties and durability (water, gas, and chloride transport and frost resistance).

Durability.

Water transport. Water transport is usually evaluated by water penetration, capillary suction and water vapour diffusion tests. Water transport estimates the potential ingress in the concrete of the liquid phase containing different aggressive substances, which can cause deterioration of the concrete and reinforcement. Also it is an indication of the concrete moisture content, which is directly correlated with the impact of freezing-thawing on the concrete.

Chloride transport. Chloride transport is essential for the corrosion resistance of the concrete's reinforcement in cases where the concrete surface is attacked by salt-water solutions. A concrete with fine pores and a low total porosity guaranties a longer lifetime of a structure. This is of a grate importance for marine and other civil engineering structures.

Frost resistance. Deterioration of concrete containing moisture subjected to freezing-thawing cycles takes place due to the 10 % increase of ice volume in comparison with the initial water volume. Frost resistance is usually improved by reduction of the water to cement ratio (total porosity) and by introduction of air-entrained admixtures. These admixtures create an organised pore structure, which release the damaging pressure of the freezing water in the concrete matrix and increase the material durability.

Carbonation. Carbonation is an important issue for external structures produced with concrete with relatively high water to binder ratios (about 0.60). The measures to be taken in design are reduction of the water to binder ratio and/or adjustment of the reinforcement cover thickness.

Carbonation of concrete takes place when the carbon dioxide, CO_2, present in the atmosphere, reacts in the presence of moisture with hydrated cement minerals. Calcium hydroxide, $Ca(OH)_2$, then carbonates to calcium carbonate, $CaCO_3$, but other cement compounds are also decomposed. Carbonation is chemically possible even at such a low pressure of carbon dioxide as in normal atmosphere. However, the increase of carbonation depth beyond the exposed concrete surface is very slow. Carbonation my cause depassivation of reinforcement of steel in the concrete due to the fact that it neutralizes the alkaline environment of the hydrated cement paste.

SINTEF

Appendix 2. Summary of SINTEF test results

<table>
<tr><td rowspan="2">**SINTEF Civil and Environmental Engineering**
Cement and Concrete

Address: N-7034 Trondheim NORWAY
Location: Richard Birkelands vei 3
Telephone: +47 73 59 52 24
Fax: +47 73 59 71 36

Enterprise No.: NO 948 007 029 MVA</td><td colspan="5">**MEMO**</td></tr>
<tr><td>MEMO CONCERNS
EMC Binders
Brief Outline of Test Results</td><td>FOR YOUR ATTENTION</td><td>COMMENTS ARE INVITED</td><td>FOR YOUR INFORMATION</td><td>AS AGREED</td></tr>
<tr><td>FILE CODE | CLASSIFICATION: Restricted
ELECTRONIC FILE CODE
S:\2271\PRO\22M098\EEJSB003.DOC</td><td>DISTRIBUTION
Vladimir Ronin
Ivar Holand
Per Arne Dahl</td><td>
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<tr><td>PROJECT NO.: 22M098.30 | DATE: 1998-08-28</td><td>PERSON RESPONSIBLE / AUTHOR
Erik J Sellevold</td><td colspan="4">NUMBER OF PAGES
4</td></tr>
</table>

INTRODUCTION

SINTEF (see attachment A for SINTEF background, attachment B for Sellevold's vita) has been engaged by EMC Development AB of Sweden to design and carry out a test program to document the properties of concrete made with cement from a new production process developed by Dr Vladimir Ronin.

The test program was designed to include tests on concrete production properties, compressive strength and durability properties. The program also included reference mixes based on OPC (ordinary Portland cement) in order to compare the performance of the EMC-blend concretes to concretes using OPC.

The approach was based on prEN 206 (proposed European Standard), which uses the "equivalent performance" (or k-value) concept to assess the effect of additions on concrete. The k-value expresses the total effect (physical and chemical) of an addition with respect to a given concrete property, relative to OPC.

The EMC production process involves very energetic grinding of the OPC-filler combination. The k-value calculation assumes that the OPC-portion in the EMC-blends has the same properties as the parent OPC, and assigns any difference between a reference OPC-mix and an EMC-mix to the filler fraction alone.

A detailed report is presently being prepared by SINTEF and will be finalised in September 1998. In the meantime the following is a summary of the results of the test program. Note that this summary is made before the detailed report is started. Hence, some minor adjustments may be necessary later.

SUMMARY

EMC-blends containing 20 % quartz filler (EMC-20) and 50 % quartz filler (EMC-50) were tested. The results of the tests and analyses that have been performed show that:

- The EMC-process has a remarkable effect on the performance of the combination OPC-quartz filler, compared to the effect of simply replacing equivalent amounts of OPC by a quartz filler.

- The EMC-technology enhances the performance of traditional additions such as limestone and blast furnace slag in concrete, thus permitting increased dosages without impairing concrete properties. In addition it permits the introduction of new microfillers such as quartz sand.

- Although tests have not been performed so far at SINTEF it is anticipated that the EMC-technology may also open doors for other types of fillers including "recycled" concrete, granite and gabbro, as well as reactive additions such as pozzolans.

More specifically:

Parameter	Standardised method of testing	k-value of quartz filler in EMC-blends
Properties of fresh concrete	NS 3662 (ISO 4109), NS 3664 (prEN 1015-13)	1)
28 days compressive strength	ISO 4012	1.4–1.8 (EMC-20), 0.6-1.2 (EMC-50)
Capillary suction and porosity	SINTEF-procedure, KS70 110	> 1.0
Carbonation	"Accelerated SINTEF Carbonation Test"	0.5-0.8 (EMC-20), 0.5-0.6 (EMC-50)
Water vapour diffusion	Nordtest Build 443	> 1.0
Resistance to water penetration	ISO/DIS 7031	> 1.0
Chloride permeability	Nordtest Build 443, ASTM C 1202 and Nordtest Build 355	> 1.0
Frost resistance	Nordtest Build 376	2)

1) The tests showed that concrete production properties of the EMC-mixes did not differ significantly from reference OPC-mixes
2) The tests showed that frost resistance may be achieved with proper air entrainment, in line with normal procedures for OPC-concrete

Note that k = 1 shows equal performance, k greater than 1 better performance, and k lower than 1 lower performance of the EMC than the reference OPC. *However, all values higher than 0 are remarkable, since k = 0 is the usual assumption for an inert filler.*

For comparison, also note that prEN 206 specifies k-values for Fly Ash as addition to concrete to be in the range 0.2 – 0.4.

The table shows that both EMC-blends perform equal to or better than OPC in all tests except carbonation.

Elaboration:

- *The fresh concrete properties* are vital in that they are the production properties of concrete during construction. As stated, these do not differ significantly from OPC-concrete although slightly different dosages of water reducing admixtures are required.

- *Compressive strength at 28 days* is the main criterion for structural design. The results indicate that EMC-20 performs better than OPC, while EMC-50 performs in a range around OPC. As with OPC and traditional blended cements, actual concrete strengths must be tested to fine-tune mix proportions when a given strength is required.

- The 6 tests of *transport properties of water and chlorides* showed that both EMC-20 and EMC-50 were more efficient than the parent OPC was (k > 1.0). These very accelerated tests are meant as indicators of durability. The fact that they all lead to the same conclusion means they reinforce each other, but it must also be noted that such accelerated tests do not necessarily predict field performance under natural exposure conditions. The frost/salt-scaling results indicate that frost resistance may be achieved by proper air content in line with normal concrete.

- *The carbonation resistance* tests show that the EMC-blends perform worse in concrete than OPC. However, the EMC concretes show performance in line with traditional blended cements (see ENV 197-1) which have been commonly used for manufacturing of reinforced concrete structures for more than 50 years with positive results.

IMPACT OF EMC-TECHNOLOGY

SINTEF has not been engaged to perform any study on economic or environmental impact of the introduction of the EMC-technology in the cement/concrete production.

Nevertheless the results of the tests are such that it is deemed appropriate to make a few observations as to some obviously unique contributions of the EMC-method.

Examples:

- During production of one tonne of clinker for OPC, ca one tonne of CO_2 gas as well as other polluting gases are emitted into the atmosphere in the most efficient cement plants. The EMC-technology significantly reduces the need for OPC production and thus the emission of such polluting gases.

- By being able to increase the use of fillers, cement can not only be produced with lower pollution but using increased amount of recycled materials that are wastes in other industries (slags, fly-ash, concrete, etc) may contribute further to the reduction of cement industry pollution as well as pollutions from other industries such as steel industry, energy producers, construction, etc.

- By replacing OPC production with low cost fillers, better cement production profitability can be achieved.

CONCLUSIONS

- EMC-blends can be used to produce concrete with production properties and compressive strengths in line with concretes produced with OPC and traditional blended cements in common use.

- In significant areas (gas and liquid permeability), important for durability, EMC-blends perform in line with, or substantially better than OPC. The areas in which EMC-blends perform better are important in many applications such as engineering structures (bridges, tunnels, roads etc) as well as marine constructions, constructions for chemical industries, structures for nuclear and other hazardous wastes. EMC-blends also have promise for High Performance Concrete.

- With respect to carbonation, EMC-blends perform lower than OPC, but in line with traditional blended cements. This fact should be taken into consideration in design.

- Significant economic potential.

- Significant environmental value.

FINAL STATEMENT

The obtained results with concretes produced with EMC blends are according to SINTEF's opinion sufficient for submittal to national bodies for acceptance of EMC as a binder in concrete(specification, certification, standardization, agrément etc) in Norway, Sweden and other EU-countries that are members of the European Organization for Technical Approval (EOTA).

Appendix 3. Tables A3-1 to A3-4, and Figures A3-1 to A3-7. (Based on tests at SINTEF in Trondheim, Norway,.see Dahl and Haugen 1998, 1999).

Table A3-1. Results from testing of fresh concrete

Mix No	Binder type (marked)	W/b-ratio Of the concrete	Concrete temp, °C	Consistency, mm		App. density, kg/m^3	Air cont. %
				Slump	Spread		
1	OPC (S1*)	0.45	21	110	420	2420	2.0
11		0.50	21	90	390	2410	2.2
21		0.60	21	105	425	2400	2.1
2	EMC-50 (S2)	0.45	21	85	395	2380	2.1
12		0.50	21	90	390	2390	1.9
22		0.60	21	80	370	2400	1.5

Table A3-2. Setting time and heat of hydration

Mix No	Binder type (marked)	w/b-ratio of the concrete	Time of setting, hours-min		Isothermal heat release, kJ/kg binder	Adiabatic temperature increase, °C
			Registerd	equ 20°C		
1	OPC (S1*)	0.45	4-20	4-50	328	49
11		0.50	4-00	4-30	342	45
21		0.60	4-00	4-30	361	39
2	EMC-50 (S2)	0.45	3-50	4-40	316	47
12		0.50	4-40	5-00	277	35
22		0.60	4-50	5-10	281	29

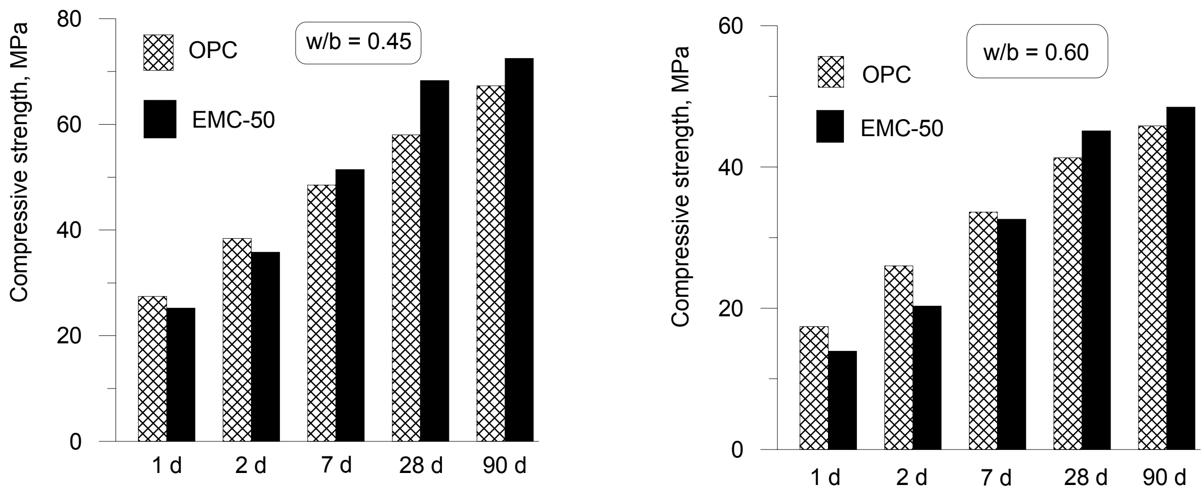
Binder type (marked)	w/b-ratio	k-value
EMC-50 (S2)	0.45	0.94
	0.50	0.62
	0.60	0.56

Table A3-3.

k-values of quartz-filler of EMC-50 with respect to heat liberation at different w/ b-ratios of the concrete

Table A3-4. Results from the testing of chloride permeability (ASTM C 1202 – 94)

Mix No	Binder type (marked)	w/b-ratio	Average value of ”Charge passed” and (SD) (Coulombs)	Evaluation of chloride permeability
1	OPC	0.45	3734 (165)	Moderate
11	(S1*)	0.50	4030 (135)	High
21		0.60	4828 (448)	High
2	EMC-50	0.45	763 (62)	Very Low
12	(S2)	0.50	821 (39)	Very Low
22		0.60	976 (106)	Very Low
3	EMC-20	0.45	1271 (141)	Low
13	(S3)	0.50	1397 (55)	Low
23		0.60	1649 (185)	Low



a) w/b = 0.45 b) w/b = 0.60

Figure A3-1. Compressive strength tests (100 mm cube) according to NS 3668 and NS 3669 (ISO 4012)

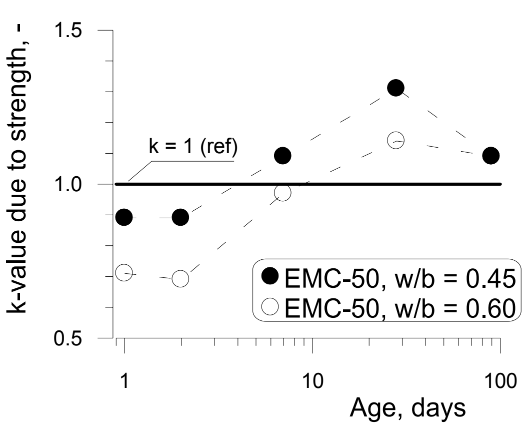


Figure A3-2.

k-values from compressive strength tests according to NS3668 and NS 3669 (ISO 4012). Absolute values, see figure A3-1.

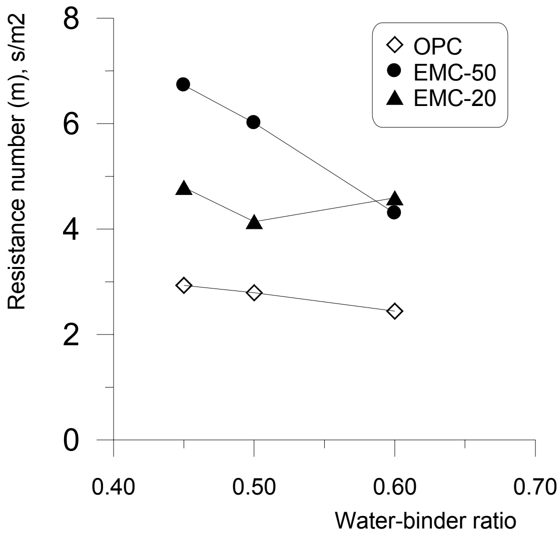


Figure A3-3. Capillary suction tests according to SINTEF-tests procedure KS70 110

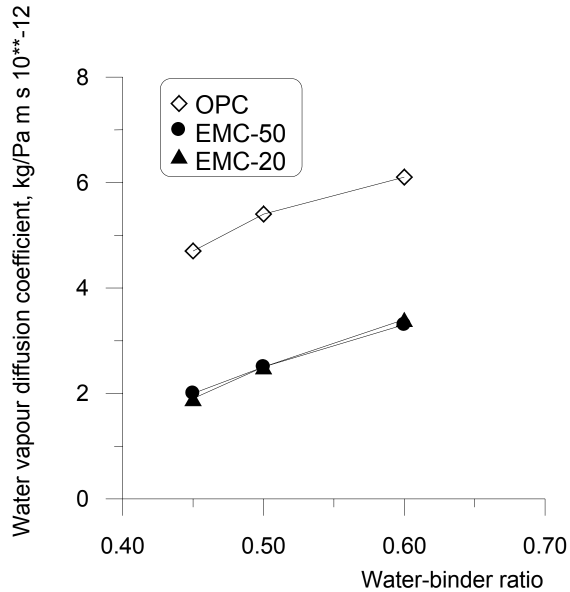


Figure A3-4. Water vapour diffusion according to Nordtest Method NT BUILD 369

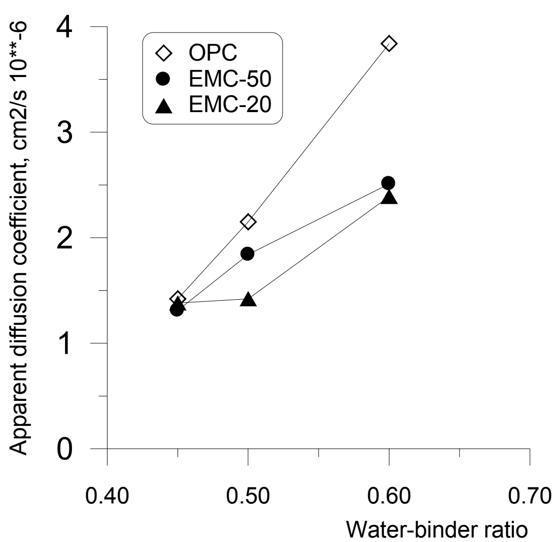


Figure A3-5. Chloride permeability tests according To Nordtest Method NT BUILD 355

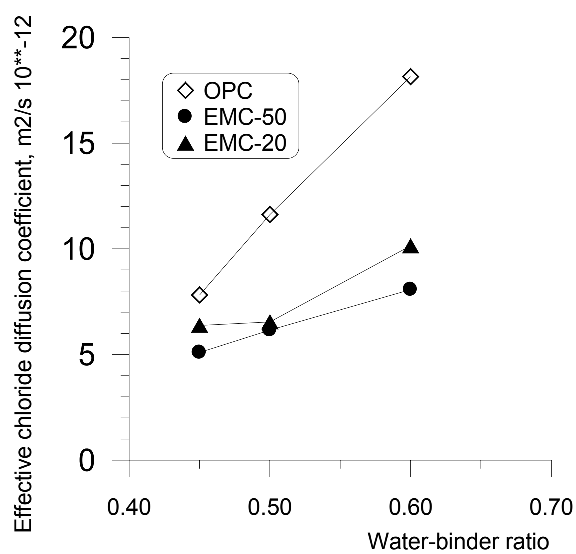


Figure A3-6. Chloride diffusion tests according to Nordtest Method NT BUILD 443

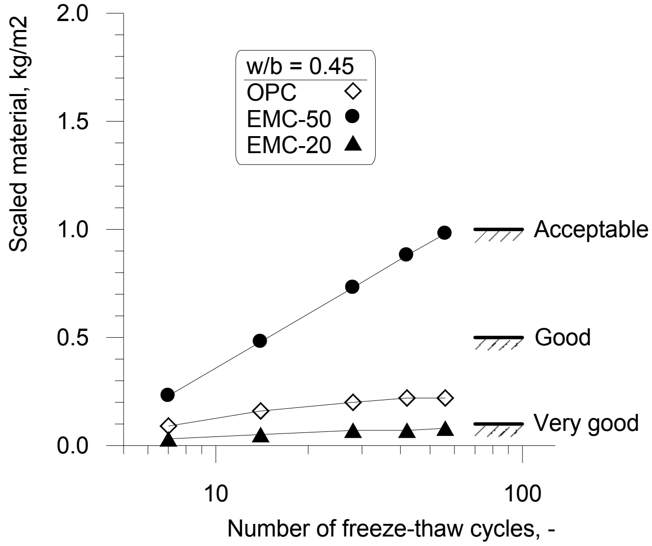


Figure A3-7.

Freeze-thaw resistance of concrete according to Nordtest Build 376 / Swedish Standard SS 137244

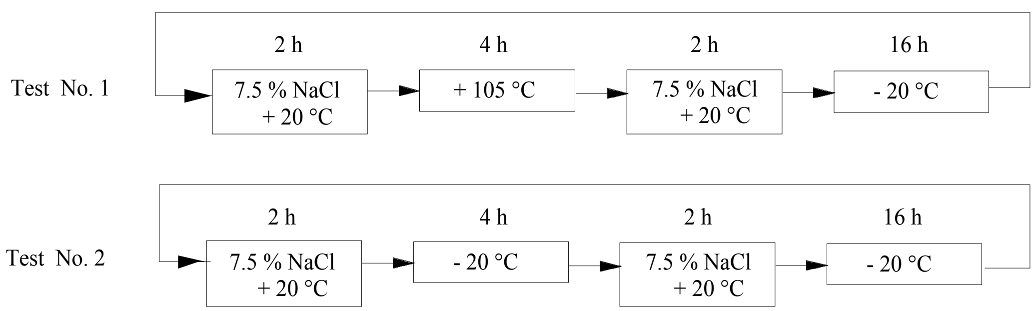


Figure A3-8. Scheme of the salt-frost resistant tests shown in figure A3-9. Tests at LTU.

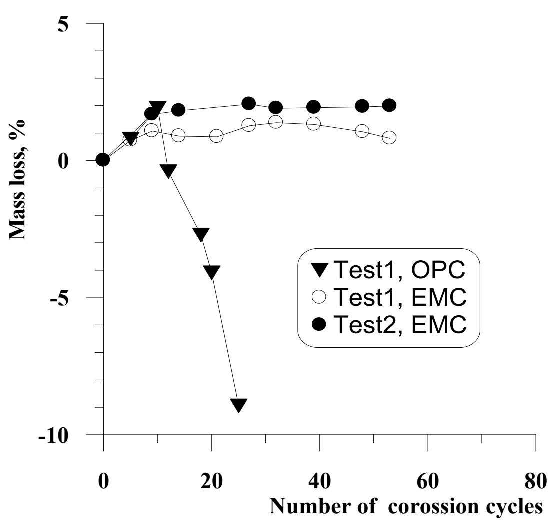


Figure A3-9.

Salt-frost resistance with the test scheme of figure A3-8. Tests done at LTU.

Appendix 4. List of the reference objects.

REFERENCE PROJECTS

Cement has been produced according to the EMC method since 1995 using a small pilot plant of 1 ton per hour capacity. In total some 2,500 tons cement has been produced.

Reference projects have been chosen to gain a broad experience with the performance characteristics of EMC cement in industrial projects. This includes not only a wide variety of applications, but also the exposure of EMC concrete to the harsh climates of northern Sweden.

Casting with EMC cement can be done in very cold temperatures of about minus 20 °C (minus 4 Fahrenheit).

These projects confirm the competitive and in cases superior performance of EMC cement over ordinary Portland cement (OPC).

The projects selected for this document are not a complete list of all projects undertaken but give a good picture of the diversity of challenges to which the EMC cement has been exposed.

Bridge over river Matojoki, Karungi in northern Sweden in 1998

Cement type : EMC-50 with 50% ordinary Portland cement and 50% fine quartz sand of size 0-2mm.

Customer : Swedish Road Administration (Vägverket).

Constructor : Skanska AB (major international construction group and until recently majority owner of Scancem, Europe's 6th largest cement producer).

Concrete : Volume about 250 m^3; designed 28-day strength of the concrete 45 MPa.

Mix design :

- EMC cement content 480 – 530 kg/ m^3,
- water to cement ratio, w/c = 0.37 – 0.40,
- amount of entrained air ca 5.6%,
- amount of superplasticizer ca. 0.5% by cement weight.

Note: These are the recommendations of Swedish Road Administration also for concretes using ordinary Portland cement

Experience

Workability : concrete mix had a slump during casting about 120 mm and showed very high sensitivity to vibration (with only slight vibration the concrete performed almost as self-compacting concrete).

Strength : the 28-day compressive strength was 60 – 62 MPa,

Frost resistance: Was tested according to Swedish National Standard (with 3% of chloride solution) and showed mass loss after 56 cycles 0.15 kg/ m^3 (upper limit 1.0 kg/ m^3).

Surface and Appearance : The surface of the concrete is very smooth, without any cracks and defects. The concrete had a light grey colour similar to concrete structures produced with white cement.

Benefits (examples)

- High level of strength development with 50% reduction in Portland cement content.
- Relatively low heat liberation and low thermo cracking propensity.
- Reduced volume of Portland cement offering a more environmentally friendly product.
- High level of workability.
- Increased sulphur resistance.
- High level of frost resistance.
- Attractive surface appearance compared to Portland cement

Shotcreting (wet mix process) (Sweden 1997-1998)

Cement type : EMC-50 cement containing 50% ordinary Portland cement and 50% fine quartz sand of size 0-2mm

Customer : LKAB, Sweden (Leading iron ore producer)

Constructor : KGS AB

Project : Shotcreting (wet mix process) with EMC cement for tunnel linings in iron ore mines at Kiruna and Malmberget in Northern Sweden.

Shotcrete : Volume of EMC cement about 100 tonnes covering a shotcreting area of about 4000 m^2.

Mix design :

- EMC cement content 450 kg/ m^3,
- water to cement ratio 0.45,
- silica fume content 35 kg/ m^3,
- plasticizer content 0.3% by cement weight,
- designed 3 day compressive strength at curing temperature 8 degrees Celsius > 20 MPa.

Experience

Workability & placement properties : Shotcrete with EMC-50 showed excellent rheological performance without any gluing effects. The shotcrete also showed practically no rebound in comparison with 10 – 15% of rebound when ordinary Portland cement was used.

Strength : 28-day strength and adhesion to the rock surface are in line with the one produced with ordinary Portland cement..

Benefits

Due to excellent workability and no rebound effect for shotcreting with EMC-50 cement, it is possible to reduce by up to 30 % the silica fume content and up to 20% the plasticizer content in the concrete mixture. EMC shotcrete showed no scaling during blasting.

Concreting foundation for ready mix concrete factory (1996-1997)

Cement type : EMC-50 cement containing 50% ordinary Portland cement and 50% fine quartz sand of size 0-2mm.

Customer : Betongindustri AB, a wholly owned subsidiary of Scancem Group, Europe's sixth largest cement producer.

Constructor : Betongindusrti AB

Project : Concreting the foundation of the new RMC factory in Stockholm, Sweden.

Concrete : Total volume of concrete about 100 m^3 with design 28-days compressive strength 50 MPa.

Mix design :

- cement content 370 to 570 kg/m^3,
- water to cement ratios from 0.45 to 0.35.

Workability : Slump of concrete mixture was about 120 mm, which is in line with workability of the concrete of the same mix design produced with ordinary Portland cement.

Strength : 28-day compressive strength 45 – 60 MPa.

Frost resistance: Tested according to Swedish National Standard (with 3% chloride solution) the concrete showed mass loss about 0.15 kg/ m^2 after 56 cycles.

Appearance : Concrete had light grey colour.

Road stabilisation projects in the Northern Sweden, 1998

Cement type : EMC-50 cement containing 50% ordinary Portland cement and 50% fine quartz sand of size 0-2mm.

Customer : Swedish Road Administration (Vägverket)

Constructor : Vägverket Produktion AB

Project : The stabilisation project included i) mixing EMC-50 cement with fine fractions of local soil material, and ii) compacting the mixture with rollers. Thickness of the stabilised layers was 0.5 to 2.0 m.

Mix Design :

cement contents 70 to 120 kg per m^3,
moisture contents 7 to 10%.

Strength : 28-day compressive strength of the ”stabilised” material 10 – 15 MPa.

Performance : After one winter, the part of the road using the EMC method of stabilisation was significantly better than the part where it was not used.

Benefits

The EMC method of stabilisation offers significant environmental and economic benefits.

In traditional road stabilisation operations, up to 3 meters of the roadbed needs to be replaced with new stabilisation materials such as concrete. The existing material needs to be removed and transported to a storage area where it is handled according to environmental requirements.

The EMC method combines EMC-cement with a new method of stabilisation which makes it possible to reuse the existing road bed material by mixing it with EMC cement and compacting with rollers.

The EMC method of road stabilisation has been tested in the harsh climate of northern Sweden, where the temperature difference between winter and summer can range between minus 40 degrees centigrade (or Fahrenheit) and plus 30 degrees centigrade (90 degrees Fahrenheit).

Bridge on highway E4, Stockholm – Haparanda, span ca 25 m, 1997

Cement type : EMC500 (95% ordinary Portland cement and 5% of silica fume)

Customer : Swedish Road Administration (Vägverket)

Constructor : Vägverket Produktion AB, Sweden

Concrete : Volume of concrete about 520m^3 (total volume of cement delivered about 180 tons).

Mix design :

- Cement content 320-370 kg/ m^3,
- w/c = 0.53,

Strength : 28-days compressive strength ca 60 MPa.

Benefits

EMC500 cement permits the reduction of binder content in the concrete up to 30% without reduction of strength

Pumping station for drinking water, Sweden, 1995

Cement type : EMC500 (95% ordinary Portland cement and 5% silica fume

Customer : Luleaa Municipality, northern Sweden

Constructor :Nåiden Bygg AB

Cement : Volume of cement delivered about 150 tonnes

Mix design :

- Cement content: 270 kg/ m^3,
- silica fume content 15 kg/ m^3,
- superplasticizer content 0.6 % per cement weight,
- water to cement ratio 0.60

Workability : Slump 120 – 150 mm

Strength : 28-day strength 48 – 50 MPa, 3-years strength ca 60 MPa (samples were drilled out of the structure).

Permeability : The concrete had very low early age water permeability (test at 8atm pressure during 24 hours), e.g. after 5 days of curing the depth of water penetration was less than 30 mm and after 14 days less than 20 mm.

Benefits

This pumping station is one of three identical units built for the Luleaa Municipality at the time. The two others were built by the same company but using ordinary Portland cement.

The unit built with EMC cement using only about 270 kg cement per m^3 concrete has shown excellent performance during 4 years of use with no leakage, no cracking, etc.

The two other units containing about 350 kg of ordinary Portland cement per m^3 concrete (about 30% more) have had to undergo cracking repair.

Foundation for Silver Museum Arjeplog, Sweden, 1995

Cement type : EMC500 (95% ordinary Portland cemen and 5% silica fume)

Customer : Arjeplog Municipality, northern Sweden

Constructor : Nåiden Bygg AB

Cement : Volume of cement delivered about 160 tonnes

Concrete characterisations are the same as for the bridge on highway E4 between Stockholm and Haparanda detailed above.

Containment pool for low concentrated sulphuric acid, Sweden 1995

Cement type : EMC500 (95% ordinary Portland cement and 5% silica fume).

Customer : Swedish Steel AB (SSAB), Luleå, Sweden, 1995

Constructor : Nåiden Bygg AB

Cement : Volume cement delivered, about 80 tonnes

Mix design :

- cement content 400 kg/ m^3,
- silica fume content 40 kg/ m^3,
- w/c= 0,40

Workability : Slump ca 80 mm

Strength : 28-day compressive strength 120 MPa.

Performance

The pool contains sulphuric acid solution with concentration of about 3.5% and temperature of about 130 °C

Normally, pools such as this would be built in concrete using ordinary Portland cement and a cover of stainless steel or acid-resistant ceramic material for protection of the concrete.

Due to the high strength and density and correspondingly very low permeability SSAB chose to use EMC concrete only, there being considered to be no need for protective measures.

Tests on the concrete after storage for 45 days in these high aggressive conditions gave about 100 MPa and the depth of penetration of the aggressive solution in the concrete was about 20 mm.

After 4 years of exploitation the pool is in very good condition, no leakage has been registered and SSAB gives very high performance rating.

Repair of floors of the pulp/paper plant in northern Sweden, 1996

Cement type : EMC500 (95% ordinary Portland cement and 5% silica fume)

Customer : SCA AB, Piteå, Sweden (one of the larges paper producers in Europe).

Constructor : Skanska and NCC, Sweden (two of Scandinavia's largest construction groups).

Cement : Volume of cement delivered, about 80 tonnes.

Project : Repair of floors of about 300 m^2 and thickness of 20 – 60 mm.

Mix design :

- cement content 330 kg/ m^3,
- w/c = 0.56,

Workability : Slump about 100 mm.

Strength : 28-day compressive strength about 60 MPa.

Performance:

The concrete is attacked by low concentrated solutions of acids and alkalis and aerosols of acids and alkalis. Concrete produced with the ordinary Portland cement in these conditions deteriorates during 2 – 3 years to a depth 20 to 40 mm.

After 3.5 years of exploitation in these very harmful conditions EMC concrete showed excellent performance without and scaling or cracking. The EMC concrete was also characterised by very high adhesion to the old concrete.

Repair of airport runway, northern Sweden, 1996.

Cement type : EMC500 (95% ordinary Portland cement and 5% silica fume)

Customer : Swedish Air Force

Constructor : EMC Production AB

Cement : Volume of cement delivered about 50 tonnes.

Project : Repair of runway of the military air base F 21, Luleå, Sweden; thickness of the new concrete was about 80 mm.

Mix design :
cement content 350 kg/ m^3,
w/c = 0.55,

Workability : slump ca 100 mm,

Strength : 28-days compressive strength 55 – 60 MPa.

Benefits: approximately 3 hours after casting the EMC concrete was subjected to a very intensive rain for about 2 hours without any damage of the concrete surface. The EMC concrete also had very good adhesion with old concrete.

High performance floors, northern Sweden, 1995

Cement type : EMC500

Customer : SSAB (Swedish Steel AB), Luleå, Sweden,

Constructor : SIAB.

Cement : Volume of cement delivered, about 50 tons

Project : Construction of floors exposed to very high mechanical abrasion in combination with high temperature 100 – 150 C (220-300 F).. Total area ca 1500 m^2.

Mix design :

- cement content 380 kg/ m^3,
- w/c = 0.42,
- fibre reinforcement,

Strength : 28-day compressive strength 80 MPa.

Benefits: While concrete produced with ordinary Portland cement usually needs to be replaced after about 1 – 1.5 year after exploitation in such conditions, the floors produced with EMC cement are still in very good condition after 4 years.

Appendix 5. Experience with EMC-50 at Bridge casting.

MEMORANDUM

Date: 15.01.2000

Prepared by: HANS HEDLUND

Experiences of EMC-50 at Bridge casting

Background

In a joint task within the Centre of High Performance Cement (CHPC) and the Swedish National Road Administration, Region North, a bridge with a span equal 16m was to be cast with approximately 200m^3 concrete using Energetically Modified Cement (EMC). The EMC binder contained 50% of fine quartz sand and 50% of Swedish Standard Slite cement (CEM I 42.5 R from Cementa AB, a subsidiary of Heidelberger Zement).

The bridge was built by Skanska AB; one of the leading construction group's in the world.

The bridge was located some 50 km south of the Polar Circle where the temperature often drops below -30°C during winter and rises above +20°C in the summer period. The transportation time from the ready mix factory was approximately 50 - 60 minutes.

Performance requirements for the concrete was as follows:

* Suitable for the use of pumping equipment
* Good workability - slump at app. 100mm on site
* Air content of 4.0 - 4.5% at site
* Frost resistance (Borås-method)
* Strength class of K55 - K60
* Topping of steel fibre reinforced concrete (SFRC)

A key performance element for casting a concrete bridge in such severe climate is frost resistance which requires the use of a well-distributed air void system. From an architectural as well as an economic point of view a high strength and slender structure was desired. Another key element to achieving a long lasting bridge is to have excellent performance during casting. This requires a good composition of the fresh concrete.

Conclusions

A comparison between laboratory tests and tests of on site casting shows that bridge concrete made of EMC-50 cement has equal performance to concrete using 100% OPC. (See table attached.)

Preliminary Laboratory testing
In co-operation with the ready-mix factory, Kallax Betong och Grus, in Kalix and Luleå University of Technology (LTU) the EMC concrete mix was designed and tested to follow the desired requirements.

Testing was done at the concrete laboratory of the Structural Engineering Division at LTU. Strength development and maturity, temperature development (generated heat), frost resistance, shrinkage, free deformation together with workability aspects were tested (see Norberg 1998).

Workability of the fresh EMC-50 concrete was designed to fit the production procedure chosen by the contractor.

Nearly 50 different fresh concrete mixes were tested to evaluate slump loss, loss of air content due to transportation, early age strength development, etc.

The optimal sieve curve of aggregate consisted of 52% gravel and 48% coarse aggregate in combination with a relatively low cement/binder content.

Tests were done using EMC-50 binder content ranging between 530 - 600 kg/m^3. Best results over all were obtained using 530 kg of EMC-50 per cubic meter concrete.

Initial slump after casting was about 180 – 200mm. Investigations showed 70 - 80mm slump loss one hour after mixing in a simulated transportation.

In the same way the air content decreased about 1.0 -1.5%.

These results are all in line with those normally achieved with 100% OPC. (See table attached.)

Bridge casting experience
During bridge casting the ambient temperature was in average -5°C and windy.

The production of the main bridge was cast using a concrete pump and vibrating sticks and the topping was cast directly on the wet main deck using a bucket and a vibrating beam. The creating personal was pleased with the remarkable good workability after such a long transportation and it was no problem to place it. The concrete had the same consistency as ordinary concrete, but behaved more like self-compacting concrete.

The site manager from Skanska remarked that the surface appearance was significantly better than for ordinary concrete. It was also appreciated that the concrete surface had a much lighter colour compared with ordinary bridge concrete.

The strength development of the chosen concrete mix reached 75% of its 28-day compressive strength within ten days of maturity. The slight retardation in early strength development was caused by slightly higher dosages of superplastisizer used to achieve the good workability (lignosulfonate based) (0.5% in comparison with average value 0.3-0.4% by cement weight for OPC). The strength development started about 10 - 12 maturity hours after casting. The heat evolution started earlier – before the strength development - preventing the concrete from freezing thus confirming the winter concreting potential of the EMC binder.

Analysis of the heat liberation of the bridge concrete has been performed in parallel with both semi-adiabatic and adiabatic equipment. The measurements performed by Skanska at the bridge were in line with the temperature development calculated in the laboratory. The EMC-50 mix has significantly lower final value of generated heat compared with heat liberation of the base cement (Slite Std P). No thermal cracks occurred during construction work.

The frost resistance was tested according the Borås method up to 56 freeze and thaw cycles. The Borås method is periodical cycles with 3% sodium-chloride solution as the temperature changes from +20°C - -20°C and back to +20°C within a 24-hour period. The EMC-50 concrete mix had an air content of 5.3% giving good frost resistance of the bridge mix.

Measurements of the autogenous deformation indicate shrinkage of the same magnitude as high performance concrete (HPC) with the same level of water-binder ratio. This effect may be due to the amount of superplastisizer used. Thermal dilatation is of the same magnitude as for ordinary concrete mixes containing ordinary Portland cement.

About one week before casting of the main bridge and deck it was decided to use a steel fibre reinforced concrete (SFRC) topping cast on the bridge. The same requirements were set as for the main bridge. Using 60 kg/m^3 of steel fiber the slump measured 120mm after casting and 80mm one hour later.

The SFRC topping showed the same experiences as mentioned above.

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Hans Hedlund, Average test results (laboratory tests, casting tests and reference OPC concrete tests, see table A5-1.

Luleå, January 15, 2000

Hans Hedlund

Table A5-1. **Average test results of EMC and OPC concretes (laboratory tests and data from bridge casting)**

Mix type	**Binder type**	**Binder content, kg/ m^3**	**w/B**	**Slump, mm**	**Density, kg/m^3**	**Compressive strength, MPa**			
						1 d	**3 d**	**7 d**	**28 d**
Laboratory	EMC-50	530	0.38	175 - 180	2400	15-18	32	41	66
In-situ casting	EMC-50	530	0.38	180 - 200	2400	17	31	40	63
Reference (lab)	OPC	530	0.38	175 - 190	2400	18-20	30	40-45	60-65

Appendix 6. CV of authors

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General

1942	Born in Göteborg, Sweden. Married, one son born 1977 .

Education

1965	M Sc (Civil Engineering), Chalmers Univ. of Technology, Göteborg.
1971	Ph D (Concrete Structures), Chalmers Univ. of Technology, Thesis: Reinforced concrete beams loaded in combined torsion, bending and shear. A study of the ultimate load-carrying capacity.
1972	Docent (Concrete Structures), Chalmers Univ. of Technology.

Positions

1966 - 71	Research Assistant, Division of Concrete Structures, Chalmers University of Technology, Göteborg.
1972 - 73	Research Engineer, University of California at Berkeley, CA, USA.
1973 - 80	Assoc. Prof. of Structural Engineering, Luleå University of Technology.
1981 - 83	Design Engineer, AB Jacobson & Widmark, Göteborg,
1984 -	Professor of Structural Engineering, Luleå University of Technology, LTU.
1990 - 97	Dean, Faculty of Engineering, LTU. In this function member of various boards.
1997-	Head of the Department of Civil and Mining Engineering, LTU.
1997 -	Director, CHPC, Center for High Performance Cements, LTU.

Committee work - Concrete

1986 - 91	Chairman, RILEM Technical Committee 90 - FMA Fracture Mechanics of Concrete - Applications
1984 -	Member, Program Committee for Swedish Concrete Research, Chairman 1989-93
1987 -	Member CEB Task Group on Fastenings to Reinforced Concrete and Masonry Structures
1991 - 93	Convenor, CEN EC 2 - Part 1A1. Eurocode 2: Concrete Structures - Unreinforced and lightly reinforced structures
1992 -	Chairman, RILEM Technical Committee 147 - FMB Fracture Mechanics to Anchorage and Bond

Commitee work - General

1991- Founding Fellow of the Bothnian Academy, Umeå, Sweden.
Chairman 1998 - present
1992 - 98 Board Member, The Research Council of Norrbotten, Luleå.
1996 - Chairman, COLDTECH, Center for Cold Climate Technology, LTU
1996 - Fellow of the Royal Skyttean Society, Umeå, Sweden

Selected Publications

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Jan-Erik Jonasson

1948	Born in Särna (480809-7390)

Education

1973	M Sc (Civil Engineering), Royal Institute of Technology, Stockholm
1982	Lic. Tech (Bridge Building), Royal Institute of Technology, Stockholm
1994	Ph D (Structural Engineering), Luleå University of Technology, Luleå (Modeling of Temperature, Moisture and Stresses in Concrete)

Employments

1973-77	Assistant researcher at the Department of Bridge Building, Royal Institute of Technology, Stockholm
1978-79	Senior Researcher, Research Bureau of National Defense, FOA, Stockholm
1980-85	Senior Researcher (Project leader), Swedish Cement and Concrete Research Institute, CBI, Stockholm
1986-1994	Lecturer and researcher, Division of Structural Engineering, Luleå University of Technology
1995-	Ass. Professor of Structural Engineering, Luleå University of Technology
1996-	Scientific Official for LTU in two Brite-EuRam projects

Int. Committees

1982-1986	Member of RILEM TC 69 – Creep and Shrinkage of Concrete Structures
1983-1987	Secretary of RILEM TC 35 – Prediction of Moisture in Buildings
1996-	Scientific Official for LTU in two Brite-Euram projects

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Hans Hedlund

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Education

1992	Masters Degree in Civil Engineering, LTU
1996	Licentiate of Technology in Structural Engineering, LTU

Employments

1986 -1987	Compulsory Military service, officer (I20/Fo61 Umeå)
1992	Swedish National Railroad administration, Luleå
1993	Div. of Structural Engineering, LTU
1993 -	PhD student, Div. of Structural Engineering, LTU
1999 -	Skanska Teknik AB, Gothenburg (60%)

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Education

1962	Bsc Civil Eng. Worcester Polytech Inst. Mass. USA
1963	MSc Civil Eng. Stanford University, California, USA
1969	PhD Building Materials, Stanford University, California, USA

Experience:

1969-81	Assist. and Assoc. Professor Technical University of Denmark
1981-83	Technical Manager, Elkem Materials, Norway
1983-88	Senior Researcher, Norwegian Building Research Institute, Oslo
1988-	Professor of Concrete Technology, Norwegian University of Science and Technology (NTNU), Trondheim

Main fields of competence

Research on concrete materials at Universities,
Research Institute and Industry with main emphasis on:
- Pore structure, pore water – properties relationships
- Volume change and cracking at early ages
- Silica fume in concrete
- General durability of concrete

Professional memberships

Convener CEN TC104/WG9 ”Silica Fume for Concrete”, 1992-
Co-Convener CEN TC104/SCI/TG5 ”Additions for Concrete”, 1991-
Member of several RILEM technical committees
Review Board: ”Magazine of Concrete Research”, UK, 1995-
Convenor CIB, TG 8.5 ”Silica Fume in Concrete”, State-of-art Report, 1999

Publications

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